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Free-Space Optics for Fixed Wireless Broadband

Author: **Pramadityo Tjondronegoro**
Advisor: **Roger Abou-Jaoude**
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Institute for Communications Engineering (LNT)
Institute of Communication Networks (LKN)

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Abstract – The demands on bandwidth and spectral availability are endless. Many telecommunication providers have been deploying different types of access technologies, such as cable and fixed wireless, in order to fulfill the needs. In many cases, transmission using fiber optics is preferred due to their ability to send high data rates with high reliability. Free-space optics technology is an alternative to the already established fiber optics technology. The main reasons are it requires less installation time and it can save the required costs significantly compared to the implementation of fiber optics without losing the capability to send high data rates. This report will explain the free space optics as a new emerging access technology as well as its possible role in the future.

I. INTRODUCTION

Free-space optics (FSO) is a wireless line of sight technology that transmits high data rates using a narrow beam light through the air as transmission medium. This technology seems to be new for the telecommunication industries, but actually it has been used by the military and NASA for about 30 years. The history of the FSO started in the late of 1960 when Dr. Erhard Kube, a German scientist and later regarded as the father of the FSO technology, published a white paper which explained about the possibility of data transmission through the atmosphere using light beams [1].

The theory of the FSO transmission is basically the same as that of the fiber optics transmission. The main difference is that the air is used as transmission medium instead of fiber. The transmission rate may reach gigabit-per-second rates over few kilometers using the unlicensed frequencies in the order of hundreds of terahertz. This is a line of sight technology, which means that the transmitted narrow beam light is traveling through the line of sight direction between the transmitter and the receiver. Due to this property, the quality of the FSO transmission really depends on the weather conditions of the transmission line of sight. It will be difficult for the receiver to detect the transmitted beam light when the heavy rain or fog comes, even birds that are flying between the path may block the transmission.

The need for FSO is accelerated by several factors. First, more and more bandwidth is needed by the end user, which means that more data access must be provided. As a fact, the number of internet users will be increased to approximately 796 million by the end of 2005 [2]. The E-commerce is now becoming more popular, hence the service providers must provide more bandwidth to the customers. Second factor is the economic consideration. Cost is an important factor to the broadband communication industries, as they are trying to offer bandwidth using the lowest cost possible in order to increase the revenue. It has been shown that the FSO implementation is not only cheaper compared to the fiber optics, but also compare to other popular technologies like the digital subscriber line (DSL) or cable modem services [2]. The third factor is the fact that the FSO technology brings new possible services that may not be able to be fulfilled by another access technology. For example, using the FSO technology, it is possible to install a high speed data connection in a remote area within 3 days, use it for a special occasion which lasts only several hours, and then after that uninstall everything back.

This report is organized as follows: Section I is an introduction to the FSO technology, Section II explains the technical aspects related to the FSO propagation, Section III explains the FSO system design, Section IV compares the FSO to the other known access technology, Section V describes the main players of the FSO technology today as well as its prospects for the future and Section VI is the conclusion of this report.

II. THE FREE-SPACE OPTICS PROPAGATION ASPECTS

Several parameters can be used to analyze the performance of FSO transmission. These parameters can be divided into two groups: internal parameters and external parameters [3]. The internal parameters are the system-specific parameters which can be chosen in the design process, such as the optical power, wavelength, transmission bandwidth, transmitter angle of divergence, transmitter and receiver optical loss, receiver sensitivity, receiver lens diameter, receiver field of view (FOV), and the

bit error rate (BER). The external parameters are the non-system-specific parameters which are related to the environment and can not be influenced by the designer, such as the climatology of the installation location, atmospheric attenuation, scintillation, window loss, and pointing loss. All these parameters will have effect in calculating the FSO system availability.

Atmospheric attenuation is caused by low clouds, rain, snow, dust, and mainly by fog. Fog is composed from the water droplets which has diameter of a few hundred microns and can modify or even stop the traveling of the beam light due to the effect of absorption, scattering, and reflection. The attenuation caused by fog may vary from 1.5 dB/km in the clear environment to more than 100 dB/km in the very dense fog situation. The solution to combat this effect is either increasing the transmit power or reducing the distance between the transmitter and the receiver. Table I gives the attenuation corresponding to its worst case weather condition [2].

Another possible source of attenuation is the window attenuation. One advantage of the data transmission using FSO is that the transmitter and the receiver can be placed inside the building and behind the window instead of placing them on the rooftop-mounted antennas. This configuration may reduce the cost that may rise due to the installation and cabling. But the disadvantage is that the window adds additional attenuation to the transmitted beam light. Window can attenuate the optical signal from 4 percent to 15 percent of its strength [3].

TABLE I. Attenuation and Maximum Range for Various Weather Conditions

Weather Condition	Attenuation for 1550 nm (dB/km)	Maximum Range (km)
Clear air	< 1.5	> 6
Heavy rain (25 mm/hr)	5	3.2
Extreme downpour (75 mm/hr)	13	1.7
Heavy snow, light fog	20	1.25
Snowstorm, heavy fog	30	0.92
Very dense fog	60-100	0.35-0.55

Scintillation is the changing of light intensities which is occurring in the receiver. This fluctuation is caused by the changing of the atmosphere’s refraction index on a small spatial scale [4]. The changing of the refraction index is caused by the thermal changes in the atmosphere, hence the effect of scintillation gets worse during midday when the temperature is the highest and may result in high bit error rate. To overcome the scintillation effect, either a high intensity receiver with a highly dynamic range, or the implementation of multiple beam transmitters, can be applied.

Another problem of FSO system is to maintain the alignment path between the transmitter and the receiver. A typical FSO transmitter transmits a beam of light with a diameter around 5-8 cm which will spread to diameter around 1-5 m per kilometer. Ideally, this narrow transmitted signal will arrive at the narrow field of view (FOV) of the receiver, but this may not be the case since the base station where the transmitter and receiver attached might be slightly moving due to environment behavior. This alignment problem may result in low received power at the receiver and link outages, thus increasing the BER.

Depending on its frequency, the base motion which causes the alignment problem can be grouped into three classes. Low-frequency base motion has periods from minutes until months and usually caused by the thermal gradient and seasonal temperature variations. Medium-frequency base motion has periods of several seconds and is caused mainly by the wind effect. High-frequency base motion has periods less than one second and it is caused by vibrations, such as a nearby human movement.

FSO system with automatic pointing and tracking system can combat the alignment problem caused by the base motion. This system translates the base motion in such a way that the loss due to pointing error can be compensated. An FSO system with tracking performs better, but of course is more expensive than the one without tracking system.

An FSO system uses a highly sensitive and large aperture lens at the receiver in order to catch the transmitted beam light as good as possible. But the drawback is that the other light from other sources which are not related to the data transmission will also be captured by the receiver lens. This phenomenon is called the solar interference. In some cases, direct and intense sunlight coming to the receiver's field of view may cause link outages for several minutes. The placement of both transmitter and receiver plays an important role in mitigating this effect.

III. THE FREE-SPACE OPTICS SYSTEM DESIGN

Several beam light wavelength intervals have been analyzed and used for the FSO system operation. These wavelength intervals have been chosen due to their robust property against the atmosphere absorption when compared to other wavelengths, and also due to the possibility of their implementation. The first widely used beam light wavelength interval is between 780 nm and 850 nm. Using this interval, an inexpensive, reliable, and high performance light beam can be made. Silicon (Si) avalanche photodiode (APD) detectors and vertical-cavity surface-emitting laser (VCSEL) technologies can be used for the operation using this wavelength interval [3], but they usually have a lower average lifetime compared to the beam light which operates in the wavelength interval between 1529 nm and 1600 nm. The latter wavelength interval has low atmosphere attenuation and high component performance which makes it possible to implement the wave division multiplexing (WDM), however the components are more expensive compared to the former ones. Many researches are being done in order to explore the possibility of using the 10,000 nm wavelength for FSO transmission, because it is reported that the transmission using this wavelength has better fog transmission characteristics.

Laser (Light Amplification by the Stimulated Emission of Radiation) and light-emitting diode (LED) are typically used for the transmission of light beam. Most FSO systems use ON-OFF keying (OOK) as the modulation format, which means that the light "ON" represents a "1" and the light "OFF" represents a "0". Only lasers are capable of being modulated at 20 Mbit/s to 2.5 Gbit/s. FSO manufacturers usually use VCSEL for the operation in the shorter wavelengths (around 850 nm) and use the Fabry-Perot (FP) or the distributed-feedback (DFB) lasers for the operation in the longer wavelengths (around 1550 nm). Other laser types can not be used for the FSO transmission.

Detector sensibility is also important in determining the performance of the overall FSO system design. For the wavelengths around 850 nm, detectors based on Silicon (Si) material are widely used. Si receivers can detect extremely low level of light and can operate at a very high bandwidth up to 10 Gbit/s. For the higher wavelengths around 1550 nm, detectors based on indium gallium arsenide (InGaAs) technology are used because they have better detection properties compared to the Si based detectors.

Erbium-doped fiber amplifier (EDFA) and semiconductor optical amplifiers (SOAs) technologies are used to increase the output power of either single or multiple closely spaced wavelengths. The peak power is defined as the maximum allowable output power at the transmitter, which is usually twice the average power for most FSO systems because of the ON-OFF keying modulation scheme is normally used. The average power term is used to define the output power at the transmitter and to classify the safety of the equipment. The average power also plays an important role in calculating the system link margin.

A well designed FSO transmitter must be obtained in order to have a narrow transmitted beam light. This narrowness will guarantee that most of the transmitted power will be absorbed by the receiver. The measure of the beam narrowness is called the beam divergence. Two types of beams are usually used in the FSO systems: the Gaussian beam and the top-hat beam. As an example of a Gaussian beam optical transmitter, 86% of the transmitted energy is located in a radius of which the amplitude declines to 0.135 ($1/e^2$) of its peak value [3]. Alternatively, the measure of the energy can be characterized as where the radial amplitude declines to 0.368 ($1/e$) of its peak intensity. Another measurement is the full-width at half amplitude (FWHA), which is defined as 0.589 times the beam width for the Gaussian beam. The intensity falloff of the FSO non–tracking system using Gaussian beam results in a weak link performance at the edges of the beam. Another disadvantage of Gaussian beam is that its peak intensity, hence the transmitted power, is limited because of the eye-safety

classification regulation. However, the Gaussian beam is used in the FSO system with automatic positioning and tracking because the intensity changes can be used to measure the tracking error.

Another alternative to the Gaussian beam is the top-hat beam, which has an almost uniform intensity distribution over the wave front and can be obtained by using multimode optical fiber as a power transmit source. The measurement of the beam energy is done by the FWHA, which is approximately equal to 0.9 times the beam width for a good designed transmitter. Note that if the distance between the transmitter and the receiver becomes longer, the beam will have largely expanded through the transmission path, thus the receiver sees no difference between the Gaussian beam transmitter and the top-hat beam transmitter.

In order to provide a better resistance against the atmospheric attenuation, an FSO system with multiple apertures for both at the transmitter and the receiver can be used. This design can also provide link redundancy, which means that the blocking of the signal due to surrounding movements can be reduced because the probability of all paths being blocked is lower. The disadvantage of using multiple apertures comes from its implementation complexity because it is very difficult to align multiple transmits beam if multiple transmitters are used, and the light must be coupled onto more receivers if multiple receivers are used. Implementing the automatic tracking and positioning system will also be more difficult, and at the end the total cost needed will be drastically increased.

The safety of the beam light is also an important subject. High power laser beam can cause injury to the eye, and even to the skin. The wavelengths between 400 nm to 1400 nm are absorbed by the eye into the retina, hence a high laser power within this wavelengths may damage the retina. Many countries and organizations have created and defined the laser safety standards which have to be fulfilled by the manufacturers and the service providers. In general, the safety standards give guidelines about the safety of the FSO system equipments and the safety of the users. Two most important classifications are the Class 1 lasers and the Class 1M lasers. Class 1 lasers are safe under reasonably operating conditions, and the Class 1M lasers should only be installed in locations where the unsafe use of optical aids can be prevented [3].

Three important calculations needed to analyze the quality of the FSO transmission link are the calculation of the received power at the optical receiver, the link budget calculation, and the availability. Due to the atmospheric absorption and the traveling distance, the received power can be calculated using [3]

$$P_{received} = P_{transmitted} * \frac{d_r^2}{\left[d_t^2 + (D * R)\right]^2} * 10^{(-a*R/10)} \tag{1}$$

where P is the power, d_t and d_r are the transmit aperture diameter and receive aperture diameter in meters, D is the beam divergence in mrad (1/e for the Gaussian beam), R is the distance between optical transmitter and receiver in km, and a is the atmospheric attenuation factor in db/km based on the environment condition. The factors that can be controlled by the system designer are the transmit power, the transmitter and receiver aperture, the beam divergence, and the transmission distance. The atmospheric attenuation a is uncontrollable and must be obtained from site measurements.

The link budget calculation for a simple FSO system without tracking involves input power, optical system loss, geometric loss, alignment loss, and detector sensitivity. Adding and subtracting these values give us the link margin, a value showing the remaining gain available to combat the atmosphere attenuation. The geometric loss in dB can be calculated using [3]

$$G(dB) = 10 * \log\left(\frac{d_r}{d_t + (D * R)}\right) \tag{2}$$

where G is the geometric loss in dB, and other parameters are the same as in equation (1). The combination of the overall system design, component reliability, and the atmosphere condition will determine the availability of the FSO system. An FSO transmission with 99.9% availability or better is difficult to obtain due to atmosphere attenuation effect.

IV. COMPARISON OF THE FSO WITH OTHER ACCESS TECHNOLOGY

The new FSO technology is usually compared to the optical fiber technology. Optical fiber has the highest capacity and also reliability among others. It can transfer high amounts of data rate up to hundreds of Gbps, and has been used to connect countries,, continents and cities. But the implementation of fiber optics does not enjoy much success in the smaller geographic areas. According to some statistics, almost 90 percent of all office building in the US have no fiber optics access to connect them with the service provider's network [5]. High cost, high complexity, and long installation time are the reasons behind this fact. To connect buildings with fiber, investment money between \$100.000 to \$200.000 is needed while the installation time may take 1 to 2 years. FSO technology offers an interesting solution because the cost required is only ten percent of what optical fibers need, and the installation can be finished within a week.

Copper lines are probably the first mean of access technology used to connect many users in many countries and provide them with voice service. They are already available in the dense regions as well as in the rural areas. However, copper lines are not intended to transfer high speed data rates. Digital subscriber line (DSL) technology is created to extend the capability of the copper lines in order to be able to transfer higher data rates up to theoretically 8 Mbps, but the availability of DSL is limited to the distance of 5 km from the provider's central office. DSL is also not a good solution when a high rate data connection must be established within a week just for a special purpose, because establishing copper lines connection requires digging and also takes time. Implementing FSO technology is a good alternative to the copper lines.

Microwave technology is a point to point access solution which is trying to solve the problem faced by the copper lines. Microwave solutions are easier to build and do not need wirelines installation. However, the frequency bands used by microwave are licensed and are subject to interfere with each other. It means that expensive spectrum licenses must be obtained and frequency planning must be done in order to reduce interference. Local multipoint distribution service (LMDS) and multichannel multipoint distribution services (MMDS) are the point to multipoint technologies based on microwave transmissions and are distributing bandwidth from a certain central point and trying to solve the connection problem where copper lines or fiber optics are not available. But they have the same frequency interference problem as other microwave based technologies. FSO technology can be an alternative to microwave technology, because FSO solutions operates in unlicensed frequencies, avoiding the need for licensing as well as the interference problem. Fig. 1 shows the comparison between FSO and other access technology in terms of transmission rates and geographic coverage [4], and Table II shows the comparison in terms of required cost per bandwidth [2].

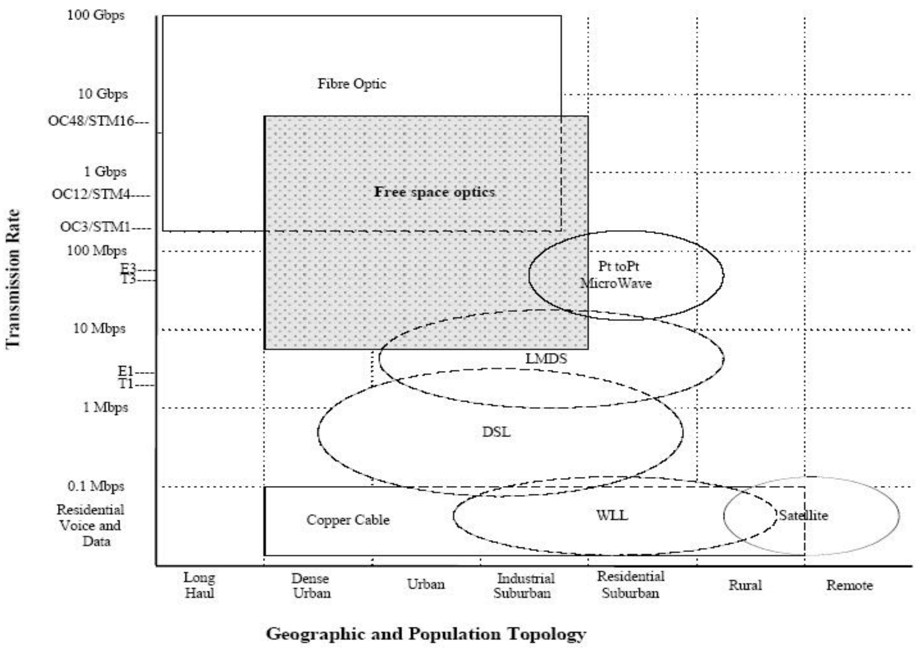

Fig. 1. Comparison of FSO with Other Technologies in terms of Bandwidth and Geographic Coverage

TABLE II. Comparison of FSO with Other Technologies in term of Cost

Access Medium	Speed (Mbps)	Monthly Cost ($)	Cost/Mbps/Month
Dial-up	0.056	20	357
Satellite	0.4	50	125
Cable Modem	1.5	50	33
DSL (minimum)	0.144	49	340
DSL (maximum)	8	1200	150
T1	1.54	350	195
RF	155	1250	8
FSO	155	555	4

FSO technology can be used together with RF systems, in the so called hybrid FSO/RF architectures, in order to increase the overall availability [6].

V. THE FUTURE OF FSO TECHNOLOGY

The FSO technology became popular as it was used to enable the Wall Street Stock Exchange back to business after the 9/11 tragedy in less than 48 hours, in an environment where fiber optics need months to be installed [7]. Merril Lynch predicts that the FSO will grow into a $2 billion market by 2005 [8]. The major manufacturers of FSO optical products are LightPointe, AirFiber, and fSONA Communications. At the moment they are trying to educate the potential customers about the benefit of using FSO solutions, and as the demand on more bandwidth become larger, FSO technology will evolve from just an alternative to the fiber optics into one of the most important access solutions. Several future FSO applications are the cellular backhaul, where FSO is used to transfer voice and data between cellular base stations, Wi-Fi hotspots, where FSO and Wi-Fi work well together since FSO provides no interference, cable TV networks, where FSO is used to transfer the digital video data, and of course as redundant links for optical fiber networks, where FSO serves as the backup link.

VI. CONCLUSION

FSO technology will be a good alternative for the fixed wireless broadband communications. It provides a high bandwidth near to the optical fiber capacity, short-time installation, and low costs. However, its dependencies on the atmospheric conditions must still be addressed in a convincing way.

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Pramadityo Tjondronegoro
pramadityo_t@mytum.de
Advisor : Roger Abou-Jaoude

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Contents

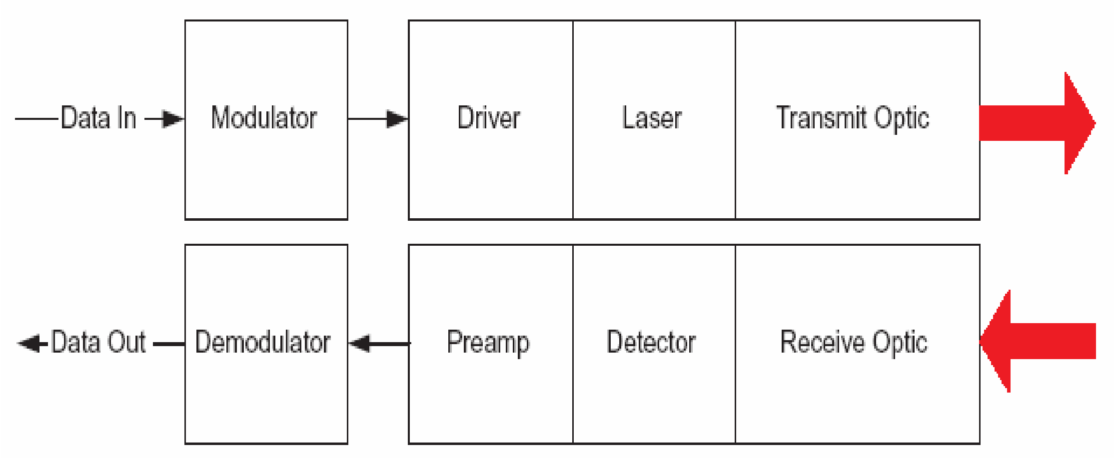
Introduction : What is FSO

- FSO: Free Space Optics.
- Idea: Transmitting data (voice, video, etc.) using narrow beam light through the space in the Line of Sight (LoS) direction between transmitter and receiver.
- Almost similar to transmitting signal using fiber optics, but here the space (air) is used as transmission medium instead of fiber.
- It provides transmission rates at the speed of light

Historical Overview

- Developed in late 60‘s by a German scientist Dr. Erhard Kube → ‘Father of FSO technology‘
- It has been used by military and NASA for more than 30 years
- Now It is seen as an alternative to the widely known fiber optics
- Enable the Wall Street Stock Exchange back to business after the 9/11 tragedy in less than 48 hours

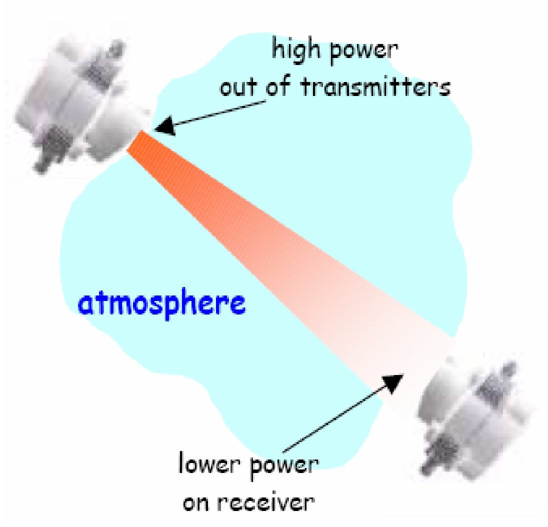
FSO System Basics (1) : Major Subsystems



FSO System Basics (2) : System Parameters

Important system parameters for reliable and efficient design are:

- Transmit power
- Transmit Beam Divergence
- Receiver Aperture Area
- Receiver Sensitivity
- Losses: Optical Loss, Geometric Loss
- Atmospheric Attenuation

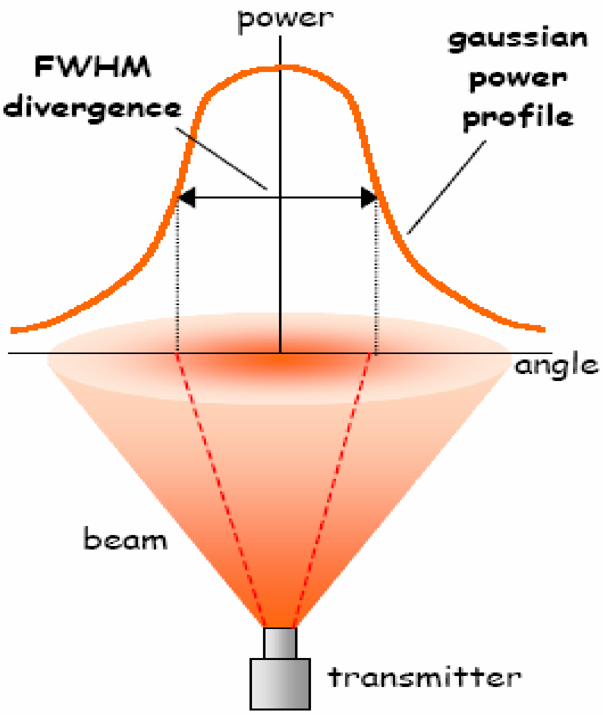


FSO System Basics (3) : Transmit Beam Divergence

Beam divergence: narrowness of the transmitted beam light.

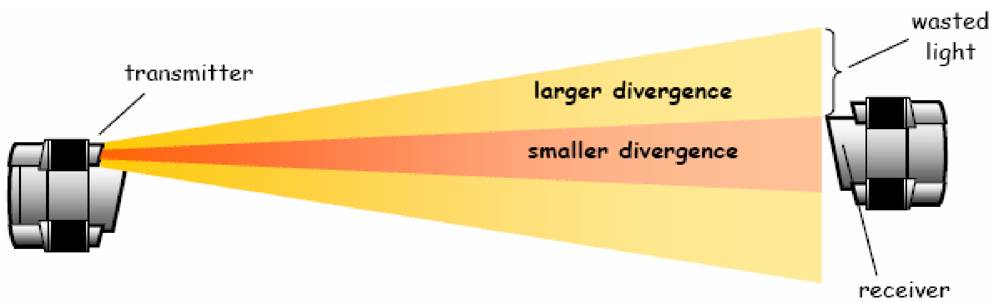
Achieved by well designed optics

Smaller beam divergence gives smaller geometric loss



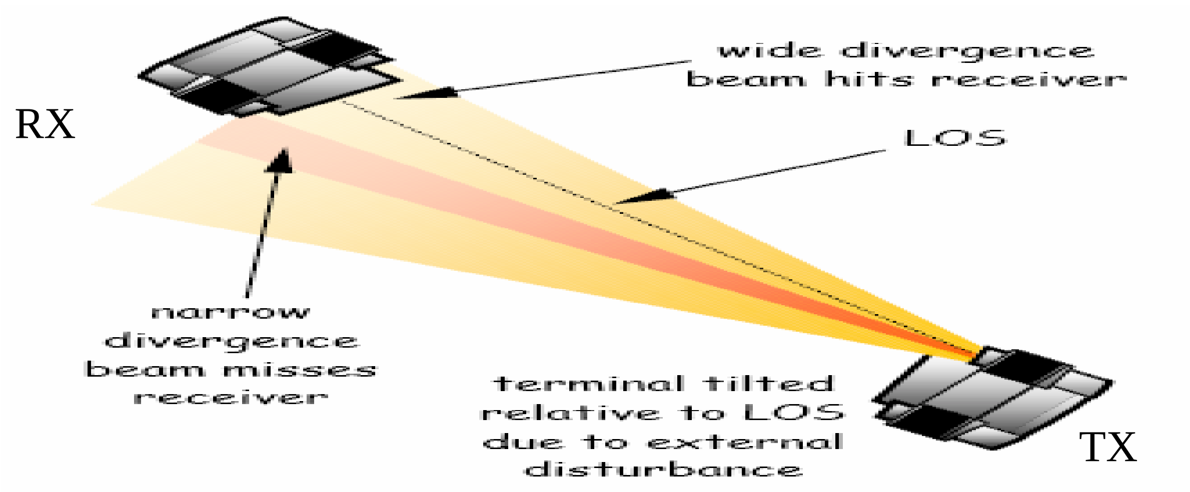
FSO System Basics (4) : Geometric Loss

Geometric loss: Loss due to the spreading of the transmitted beam light between TX and RX



$$P_{received} = P_{transmitted} * \frac{d_r^2}{\left[d_t^2 + (D * R)\right]^2} * 10^{(-a*R/10)}$$

FSO System Basics (5) : Tracking Loss



Solution: Automatic Tracking System → Overcome mismatch problem and enable to use smaller beam divergence

FSO System Design Issues (1): Link Budget Calculation

FSO system without automatic tracking system

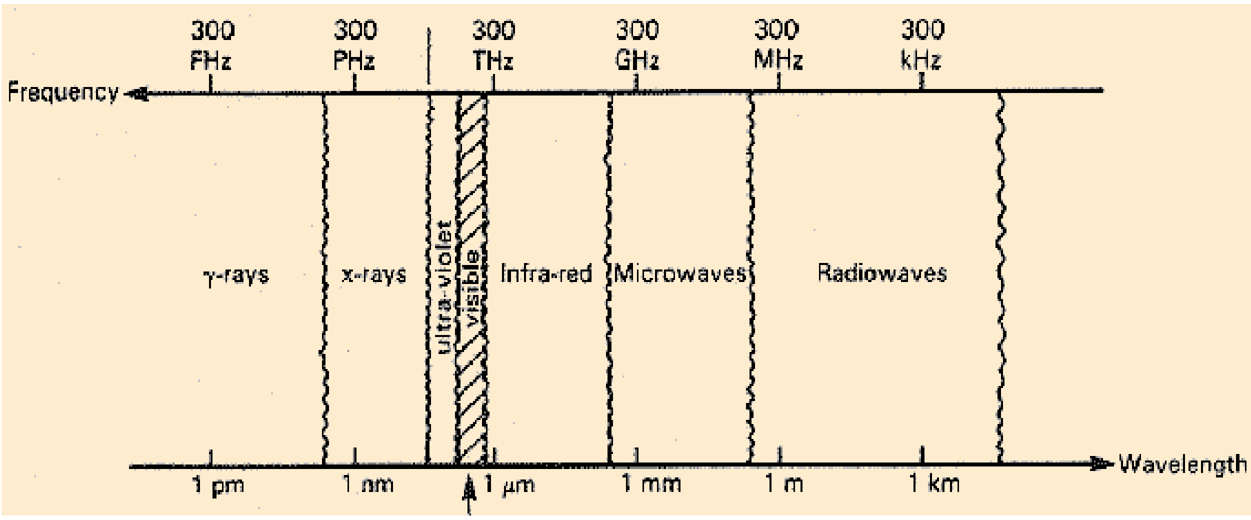
Parameter	Link Range 300 m	Link Range 2000 m	Comment
Average laser power	10.0 dBm	10.0 dBm	
System loss	−6.0 dB	−6.0 dB	Combined TX/RX terminal losses
Geometric loss	−27.0 dB	−44.0 dB	8-mrad TX divergence; 3-mrad pointing error
Signal power on detector	−23.0 dBm	−40.0 dBm	In clear air, no window loss
Detector sensitivity	−46.0 dBm	−46.0 dBm	Wavelength and data-rate dependent
Clear air link margin	23.0 dB	6.0 dB	For atmospherics and window loss

FSO System Design Issues (2): Link Budget Calculation

FSO system with automatic tracking system

Parameter	Link Range 300 m	Link Range 2000 m	Comment
Average laser power	10.0 dBm	10.0 dBm	
System loss	–8.0 dB	–8.0 dB	Combined TX/RX terminal losses
Geometric loss	–4.0 dB	–18.0 dB	0.5-mrad TX divergence; 0.15-mrad pointing error
Signal power on detector	–2.0 dBm	–16.0 dBm	In clear air, no window loss
Detector sensitivity	–46.0 dBm	–46.0 dBm	Wavelength and data rate dependent
Clear air link margin	44.0 dB	30.0 dB	For atmospherics and window loss

FSO System Design Issues (3) : Wavelengths



Chosen Wavelength:

- 780-850 nm (353-385 THz)
- 1520-1600 nm (188-197 THz)

Reason:

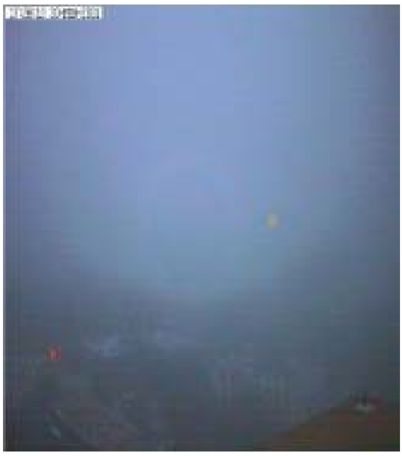
- Low attenuation
- Implementation and safety

FSO Propagations (1) : Test Case 1

Attenuation is mainly caused by fog

No Fog
Loss of 6.5 dB/km

Dense Fog
Loss of 113 dB/km



Very Dense Fog
Loss of 173 dB/km

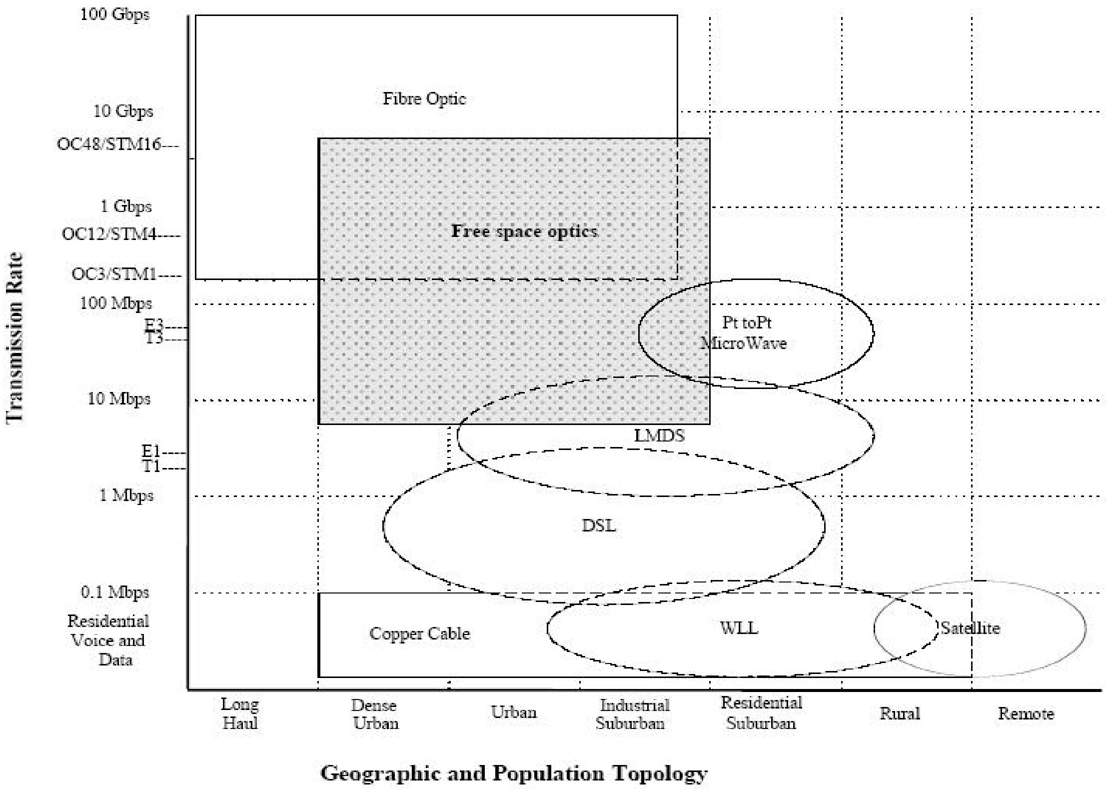
Air link margin will have to combat this loss

FSO Propagations (2) : Test Case 2

Weather Condition	Attenuation for 1550 nm (dB/km)	Maximum Range (km)
Clear air	< 1.5	> 6
Heavy rain (25 mm/hr)	5	3.2
Extreme downpour (75 mm/hr)	13	1.7
Heavy snow, light fog	20	1.25
Snowstorm, heavy fog	30	0.92
Very dense fog	60-100	0.35-0.55

FSO Propagations (3) : Comparison with Fiber Optics

FSO Comparison (1) : Rate vs Coverage



FSO Comparison (2) : Cost

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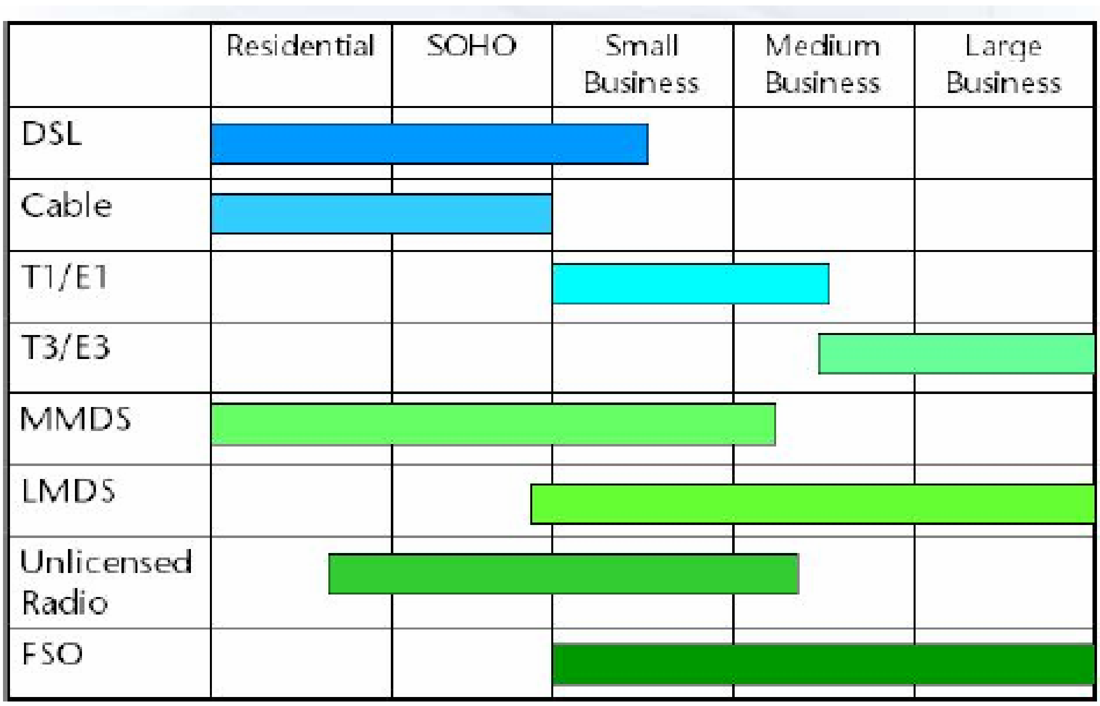
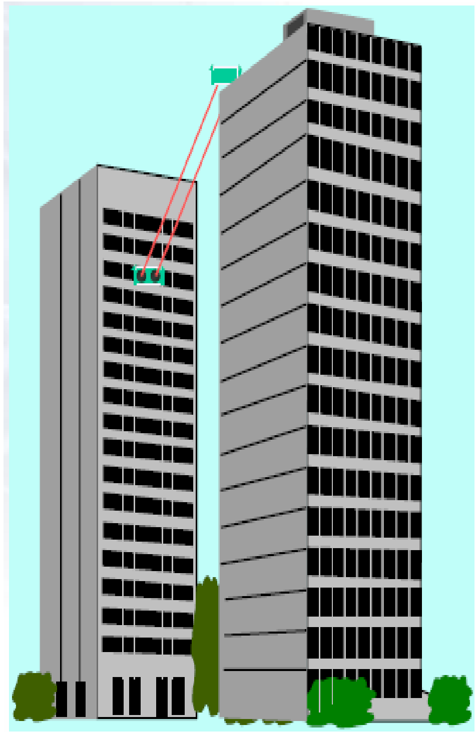
RF	155	1250	8
FSO	155	555	4

FSO Comparison (4) : Where does FSO fit?



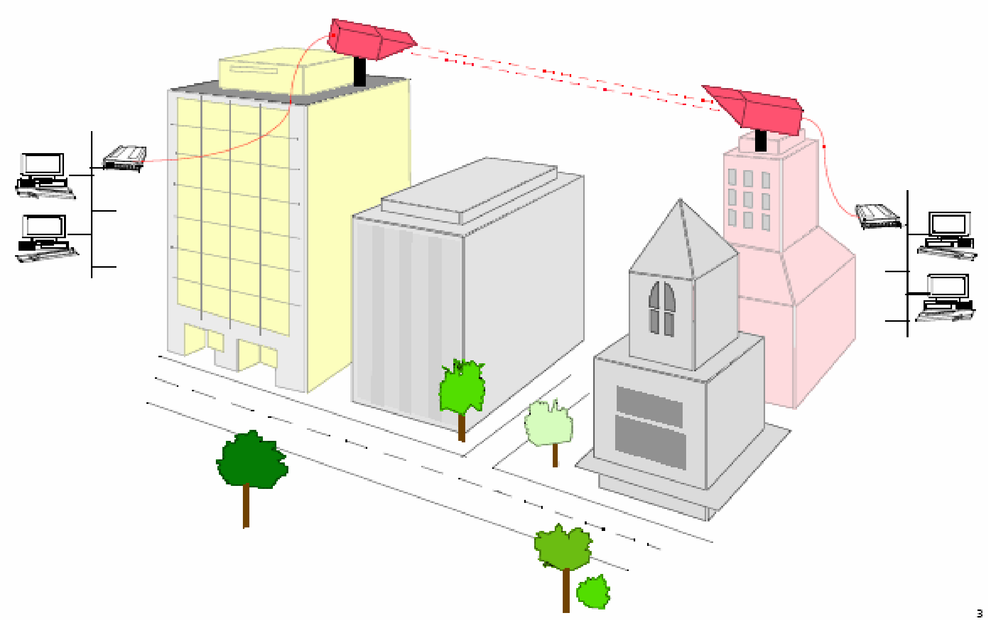
FSO Comparison (5) : Advantages

1. High rates
2. No frequency lisence required
3. Fast and easy installation
4. Distance up to kms
5. Compatible with other access technology
6. Cost effective, movable asset
7. Near zero latency over all distances
8. Transparent to networks or protocols
9. Internal and external mounting



Future of FSO (1)

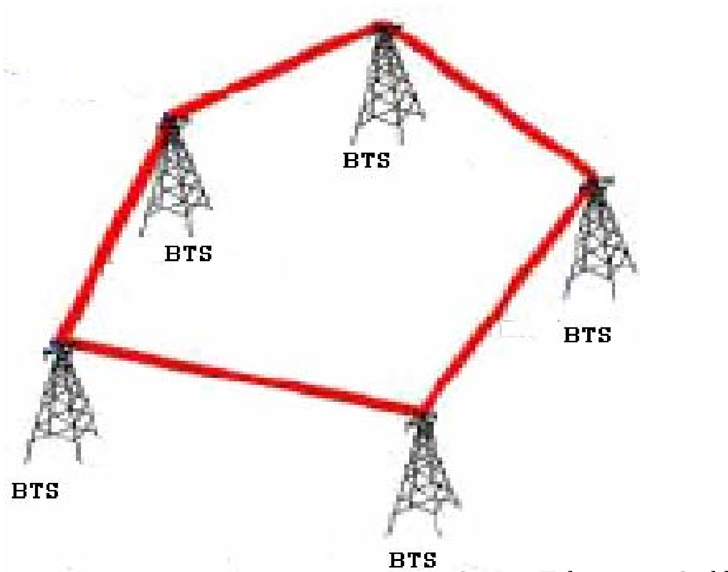
- Short distance LAN extensions



Source: Teleconnect Gmbh

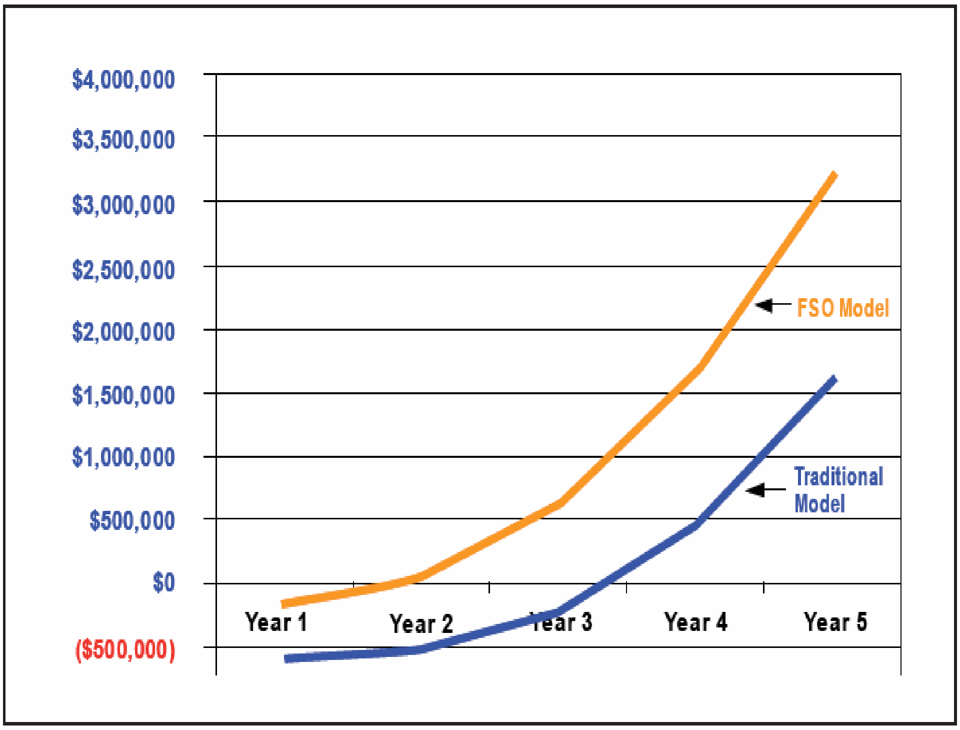
Future of FSO (2)

- Cellular / Telco backhaul network
  → Hybrid FSO/RF system



Source: Teleconnect Gmbh

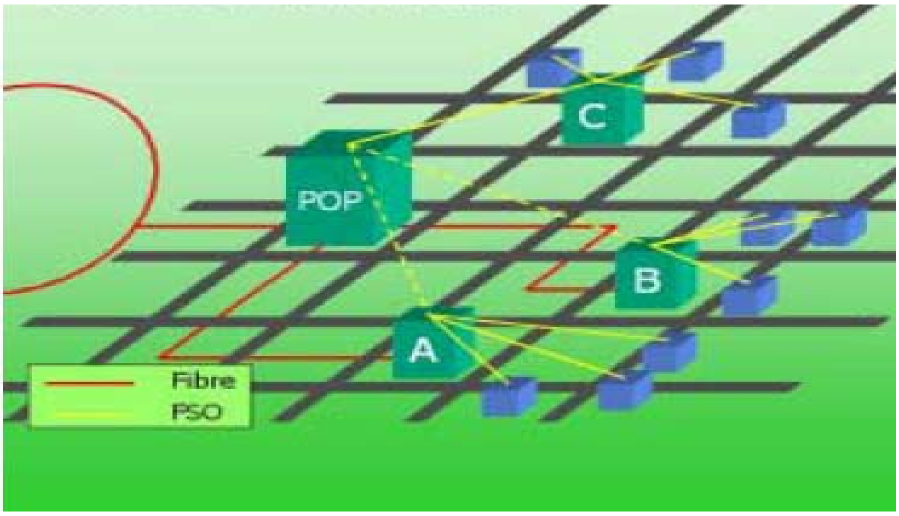
FSO Comparison (3) : Cost, a Test Case



Source: Fsona Corp

Future of FSO (3)

- Data networks in crowded urban environment and campuses, → difficult terrain
- Backup network, disaster recovery
- Temporary installment



Conclusions

1. Free-space optics technology is a good alternative, especially compare to fiber optics
2. In the future, FSO may be one of the most important access technologies due to its advantages
3. Big market in the future.
4. Note: Availability and quality really depends on the environment conditions.
5. Market education is needed.

End of Presentation

Thank You for Your Attention

Questions ?